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A Study on Application of Immobilized *Spirulina platensis* Pellets in Removal of Heavy Metals from Pharmaceutical Effluent

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Abstract

Effluent treatment through biological methods have gained attention, in particular to remove heavy metals and toxic intermediates from pharmaceutical industry was focused in this study. Using *Spirulina platensis* pellets the treated and untreated effluent were compared based on AAS analysis. In this study, Heavy metal removal study was further conducted for Lead. For the same Lead acetate (1g/100ml) incorporated with Zarrocks medium and applied for immobilized *S.platensis* cultivation. After incubation for 7 days the filtrate was collected and analyzed through Atomic Absorption Spectroscopy. The results showed lead concentration before treatment as 4.077mg/l and after treatment 1.719mg/l. Further SEM analysis was performed analysis revealed noticeable morphological changes on the surface of *Spirulina platensis* after exposure to heavy metals. The untreated cells exhibited a smooth, intact surface, while the treated samples showed irregularities, surface roughness, and the presence of particulate deposits, likely corresponding to absorbed heavy metal ions. Based on indexing method analysis, this study concluded that lead and chromium were the most effectively removed heavy metals, as confirmed by the Heavy metals Index (HMI) for *Spirulina platensis* immobilized pellets.

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Spirulina platensis; AAS; Agar; Immobilization; Effluent; HMI; HEI; HQs.

Introduction

Industrial wastewater often contains a complex mixture of toxic substances, including heavy metals (HMs), organic pollutants, and other compound that led to environmental problems such as water contamination and soil bioaccumulation (Itana *et al.*, 2025). Pharmaceutical industry produces a wide variety of products and discharges large amounts of liquid and hazardous solid waste. The liquid waste generated from this industry contains high BOD, COD, TDS and Suspended solids. Due to high BOD content, the waste on discharging into a stream rapidly depletes dissolved oxygen and renders the water unsuitable for further use.

Among different source industrial effluents, pharmaceutical industrial effluent is of great concern for the reason that more than 100 different drug contaminants have been detected in the contaminated soil, sediments, sludge, effluents released from its sewage treatment plants to groundwater, surface water and also to surrounding water ecosystem.

In many countries including waterways of North America, Canada and across the Europe frequently have been reported the presence of trace levels of antibiotics, tranquilizers, anti-inflammatory, painkillers, hormones, hypolipidemic, antiepileptic and chemotherapeutic drugs. Most of the residual chemical considered to be hazardous

due to their toxic, mutagenic, carcinogenic and genotoxic properties (Singare and Dhabarde, 2016).

Pharmaceutical effluent in untreated state do contains a high level of pollutants because of the presence of non-biodegradable organic matter and other pollutants. Discharging of untreated pharmaceutical wastewater into the natural environment causes health hazards to existing flora and fauna. Therefore, appropriate treatment of the effluents to remove heavy metals and associated contaminants prior to discharge into ecosystem are important (Shabana *et al.*, 2019).

HMs like copper (Cu), zinc (Zn) and iron (Fe) are necessary for living things to grow and develop normally. Even necessary heavy metals, though, can turn poisonous if they get into the water supply. For instance, elevated iron (Fe) levels might disengage the pumping fixtures, discolor garments, and provide a metallic taste in the water. Overly high zinc (Zn) levels can harm aquatic life by obstructing the absorption of other essential elements like copper (Cu). Elevated copper (Cu) levels in people can cause digestive problems, liver and kidney damage, and more (Preonty *et al.*, 2025). Chromium (Cr) is an acute carcinogen and more mobile and toxic than Cr is an acute carcinogen and more mobile and toxic than Cr. Human activities are responsible for contamination of drinking water by Cr. Lead (Pb) poisoning is considered to be a great threat to young children and is the number one environmental disease among children in developing countries. Long term exposure of cadmium (Cd) during fetal life has been reported to be particularly dangerous for the central nervous system. Toxic effects of mercury (Hg (II)) include damage to the brain, kidney, and lungs. (Tamilselvan *et al.*, 2011)

Biosorbents have been used for the decontamination of wastewater for a long time. Research has shown that biosorbents derived from non-living biological materials can effectively purify contaminated environments. According to experts, by 2025, half of the global population will reside in areas where water scarcity is a major worry. Roughly 785 million people do not have access to basic water purification services.

Biosorption is an emerging technology to overcome the obstacles related to conventional wastewater treatment techniques. However, the high cost of efficacious materials like synthetic polymer resins and activated carbon limits the usage of adsorption techniques on an industrial scale. (Sarangi *et al.*, 2025)

Biosorption is a passive process where microorganisms, such as microalgae, absorb and concentrate pollutants, thus removing them from the surrounding environment. *Spirulina* a blue-green microalga, adapting to versatile environment has gained attention as a potential bioremediation agent due to its remarkable ability to absorb heavy metals (Babu *et al.*, 2020). Due to its surface area, accommodating nutrient content, and natural tolerance to various environmental conditions make it an ideal candidate for heavy metal biosorption (Zhang *et al.*, 2021).

While comparing available treatment methods for heavy metal removal such as physical, chemical, and biological methods, physical method through surface adsorption is found to be effective in effluent treatment. In biological treatment by using microalgae that are capable of accommodating considerable amount of heavy metal sue to their surface: volume ratio. The ability of *Spirulina platensis* culture production on wastewater is necessary for the treatment of mining wastewater on a small-scale effluent treatment. *Spirulina platensis* is able to be adsorb pollutants and can be generated with high alkalinity which is very essential for the precipitation of heavy metals. (Randrianarison *et al.*, 2021)

There are some limitations in the application of free-floating *Spirulina* in large-scale remediation processes. First, it is difficult to separate algae from treated water for reuse either heavy metal or algae culture (Vazquez *et al.*, 2019). To overcome this, the immobilization of *Spirulina* onto solid supports has been proposed as suitable solution (Kasim *et al.*, 2017).

Immobilization refers to the process of confining microorganisms or cells to a solid substrate or matrix, which helps enhance their stability, reusability, and efficiency in bioremediation processes (De Jesus *et al.*, 2021). This method not only improves the algae resistance to adverse environmental conditions but also facilitates easy recovery and separation of heavy metal after the process (Zhang *et al.*, 2020).

Nature derived polymers are acquired from plants, microbial cultures, animals, and algae. The scientific community is paying close attention to seaweed-derived polysaccharides like alginate, carrageenan, and agar since they are widely available, biodegradable, and cost effective. Desorption and regeneration of the adsorbent material that needs chemical treatment (HNO₃, HCl, NaOH, ethanol, acetone, etc.) would be a costly process and can affect the adsorbent structural and functional

properties. This may be the cause of the shift in focus toward high-performance, affordable, biodegradable adsorbent materials. Therefore, one of the benefits of green adsorbent may be the recovery of metal ions through straightforward matrix degradation (Michalak *et al.*, 2018).

This study focused to enhance the efficacy and feasibility of immobilized *Spirulina* pellets for the remediation of polluted water with pharmaceutical industry effluent. By generating suitable method for complete heavy metal removal from industrial effluent to avoid contamination to water ecosystem and associated unwanted health hazards in near future. As an attempt, this study has focused on to contribute to the development of cost-effective, sustainable, and environmentally friendly bioremediation process for pharmaceutical industrial effluent treatment.

Materials and Methods

Algal Culture Collection

The freshwater cyanobacteria *Spirulina platensis* live culture was purchased from offerr Nallayan Spirulina research centre, Natham in a sterile plastic container. The appearance of the culture was dark green and 500 ml of culture was purchased.

Microscopic Examination

To prepare the cyanobacterial culture for examination, a drop of inoculum was placed in a clean grease free slide and covered it with a coverslip and observe under objective of the light Microscope under 45X magnification.

Cultivation of *Spirulina platensis*

Spirulina platensis was inoculated in Zarrouk's medium in 500 mL beaker containing 100 mL liquid medium under sterile condition, pH was adjusted to 9. Growth and maintenance of the culture was done in an illuminated growth room at 30 ± 2 °C under 12: 12 hour light- dark cycles. Manual shaking was done thrice a day (Dineshkumar *et al.*, 2016).

Growth curve Analysis

In Zarrouk's medium the culture was maintained and the growth curve was recorded in OD value using Digital spectrophotometer at 680 nm.

Immobilization of *Spirulina platensis*

The algal culture was centrifuged at 5000 rpm for 10 minutes, washed with distilled water and dried at 50°C for 24 hours before use. Measured amount of dry *S.platensis* biomass were suspended in distilled water. A 50 ml of distilled water and 5 gram of agar was added to this dissolved in 90°C for 2 minutes. A dried biomass was added about 2 grams stir until evenly and spontaneously placed in calcium chloride (CaCl₂) and the beads were collected and washed in distilled water (Aleksandra Duda -Chodak *et al.*, 2013).

Effluent sample collection

About 5 litre of Pharmaceutical effluent pond water sample was collected using sterile plastic bottles at Kakkalur, SIDCO industrial area. The sample was brought to the laboratory and then refrigerated at - 4 °C for physicochemical and heavy metal analysis.

Physical Characteristics of Effluent

The colour, odour, turbidity, conductivity, foaming, clarity of the collected effluent sample was observed. (Hossen *et al.*, 2024)

Physico-chemical Characteristics of Effluent

The temperature, pH,EC, and DO were measured. The other physicochemical parameters such as biochemical oxygen demand, chemical oxygen demand, total suspended solids, total dissolved solids, were analysed using the standard methods of Indian Standards (IS). (Hossen *et al.*, 2024)

Heavy Metals Analysis of Effluent

In the collected sample, heavy metal analysis including Lead, Mercury, Arsenic, Cadmium, Chromium, Zinc, Copper, Iron were analysed using Atomic Absorption Spectroscopy (AAS). According to the Environmental protection agency method as described. The concentration of metal ions of the samples were measured using the standard procedure with IS. (Anjali Patil and Mamta Arya, 2024)

Heavy Metal Analysis

In the present study the concentration of heavy metals were determined by using Atomic Absorption Spectrometer (AAS) in Centre for waste Management –

IRC Sathyabama Institute of Science and Technology. For AAS measurements, the standards solution with concentration of 1 g/L were diluted and a series of standards applied respectively.

Bioremediation of heavy metals using immobilized algal pellets

The immobilized *Spirulina platensis* about 25 pellets were added to 100ml of effluent sample. (Chodak *et al.*, 2013)

Analysis of Lead removal by *S.platensis* pellets

Zarrouk medium was prepared for 10 ml and 0.1 g of lead acetate was added and prepared, around 10 algal pellets were added and kept for 7 days of incubation. The OD value was recorded and it is analysed by AAS. (Chodak *et al.*, 2013)

Scanning Electron Microscope

SEM studies were performed using a field emission scanning Electron Microscope. (Lee *et al.*, 2015). The absorbed pellets were crushed and it was dried for 24 hours and it is given to analysis.

Indexing Methods

Water quality indices for the discharged effluent was calculated to assess the environmental impacts and the contamination levels, which are stated below.

Heavy Metal Pollution Index (HPI) analysis

The overall water quality of the treated water and its sustainability for human consumption were assessed using heavy metal pollution index (HPI) according to equation (1) (2) (3). The HPI values were calculated using the following equations

$$HPI = \frac{\sum_{i=1}^{i=n} w_i \times Q_i}{\sum_{j=1}^{j=n} w_j} \quad (1)$$

Where Q_i is the subindex of the i th parameter, W_i is the unit weight of the parameter and n is the number of parameters considered. The unit weight of the i th parameter (W_i) and the subindex (Q_i) of the i th parameter are given by the equations:

$$W_i = K/S_i \quad (2)$$

$$Q_i = ((M_i - I_i) / (S_i - I_i)) \times 100 \quad (3)$$

Where M_i is the monitored value of the metal of the i th parameter in ppm, S_i is the standard permissible in ppm and I_i is the ideal value of the i th parameter in ppm. The HPI value of water less than 100 is considered safe for drinking, while water is considered unsafe for drinking, when the HPI value of water is greater than 100 (Hossen *et al.*, 2024)

Heavy metal Evaluation Index (HEI)

The HEI analysis was done to assess the level of pollution the discharged effluent with respect to heavy metals, calculated based on Eq. (4)

$$HEI = \sum_{i=1}^n H_c / H_{mac} \quad (4)$$

Where H_c and H_{mac} are the monitored values and maximum admissible concentration (MAC) of the i th parameter in ppm, respectively. The applied parameters and constants for the calculation of HEI were done according to WHO guidelines. The proposed HEI criteria are as follows: pollution level is considered low, when $HEI < 10$, medium, when $HEI = 10-20$, and high, when $HEI > 20$.

Hazard Quotients (HQs)

The Hazard Quotients (HQs), also called Risk Quotients (RQs), is calculated using Eq. (5)

$$RQ = MEC/PNEC \quad (5)$$

Where the unit for the measured environmental concentration (MEC) and the predicted no effect concentration (PNEC) is ppm. When PNEC is not available, which is a constant for each chemical, estimated PNECs can be derived from the values of effect concentration, EC50 or lethal concentration, LC50 reported in the literature, divided by an appropriate uncertainty factor (assessment factor, AF), which varies from 10 to 1000.

The proposed RQ criteria are as follows: $RQ < 0.1$ meaning minimum risk; $0.1 \leq RQ < 1.0$ meaning intermediate risk and $RQ \geq 1.0$ meaning high environmental risk (Hossen *et al.*, 2024).

Results and Discussion

Culture collection

The culture was collected from the cultivation centre. (Fig.1)

Microscopic Examination

Microscopic observation of microalgae was observed under 45x of light microscope. (Fig 2)

Cultivation of *Spirulina platensis*

Spirulina platensis was successfully cultured in selective medium Zarrouk medium for 15 days (Fig 3). The pH was determined on the daily basis. Appearance of culture has also shifted from light green to dark green in proportion to the increasing cell mass. While the cultivation of *Spirulina* in Zarrouk medium, both the pH and appearance does not change. Microscopic and visual observation revealed that the culture was grown healthy.

Growth curve Analysis

The growth curve was recorded in daily bases and it was tabulated (Table 2). The graph was plotted (Fig 4).

Immobilization of *Spirulina platensis*

In log phase *Spirulina platensis* culture was immobilized with 5% Agar. Further random sized immobilized beads were prepared and showed in Fig. 5

Effluent collection

After collection effluent samples were stored at 4°C

Bioremediation using algal beads

Immobilization of algal beads which is used to treat heavy metals.

Indexing Methods

Heavy metal pollution Index

The HPI analysis results showed that the discharged effluent was unsafe for human consumption for domestic and drinking purposes. However, the HEI analysis for the heavy metal pollution revealed that the treated water

was in the low pollution category considering the heavy metal concentrations. The RQs analysis for mixtures of heavy metals showed that they had a high environmental risk suggested that the discharged effluent had significant environmental impacts. The WWTP managed to develop the, the HPI value by 1867.836 the HEI value by 55.113%, and $R_Q = \text{MEC/PNEC}$ value considering only eight heavy metals and metalloids by 55.113 %. Despite these developments, the discharged effluent fell under poor water quality, which was unsafe for consumption and had a high environmental risk.

This study aimed to utilize immobilized *Spirulina platensis* pellets in remediation of heavy metals in pharmaceutical effluent. For the same, Pharmaceutical effluent was collected from Kakkalur, Thiruvallur District. Likewise, the study by Affek *et al.*, 2018 declared that mixture toxicity often exceeded predictions based on independent action models, suggesting complex interactions between the substances, including potential synergistic or antagonistic effects. These findings highlight the limitations of traditional risk assessment methods, which focus on individual substances rather than their combined effects in real-world scenarios. There was an urgent need for improved environmental risk assessment frameworks that account for mixture toxicity, as pharmaceutical residues in water bodies pose a significant threat to aquatic ecosystems, potentially disrupting biodiversity and ecosystem balance.

The study found that the wet adsorbent exhibited faster removal and higher uptake than the dry adsorbent, with adsorption increasing at higher temperatures. The adsorption data fitted the Langmuir isotherm model, indicating monolayer adsorption. The primary adsorption mechanisms were cation exchange and hydrogen bonding. Overall, the study suggests that carbon derived from date palm leaflets is a cost effective and efficient material for removing ciprofloxacin from water (El-Shafey *et al.*, 2011).

Agar is a sulphated galactan obtained from some species of red algae. The major gel forming component of agar consists of a linear chain of sequence of (1-3) linked-β-D- Glucopyranosyl units and (1-4) linkages to 3,6-anhydro-α-D-Galactopyranosol units. Agar is a thermoreversible gel. This polymer is best suitable for immobilizing microalgal cells. Agar melts around 85°C and solidifies between 30 – 45°C. Species able to withstand short thermal shock of this level should be selected for agar immobilization.

Fig.1 *Spirulina platensis* Culture collection



Fig.2 Microscopic observation



Fig.3 Zarrouk's medium



Fig.4 Growth curve of *Spirulina platensis*

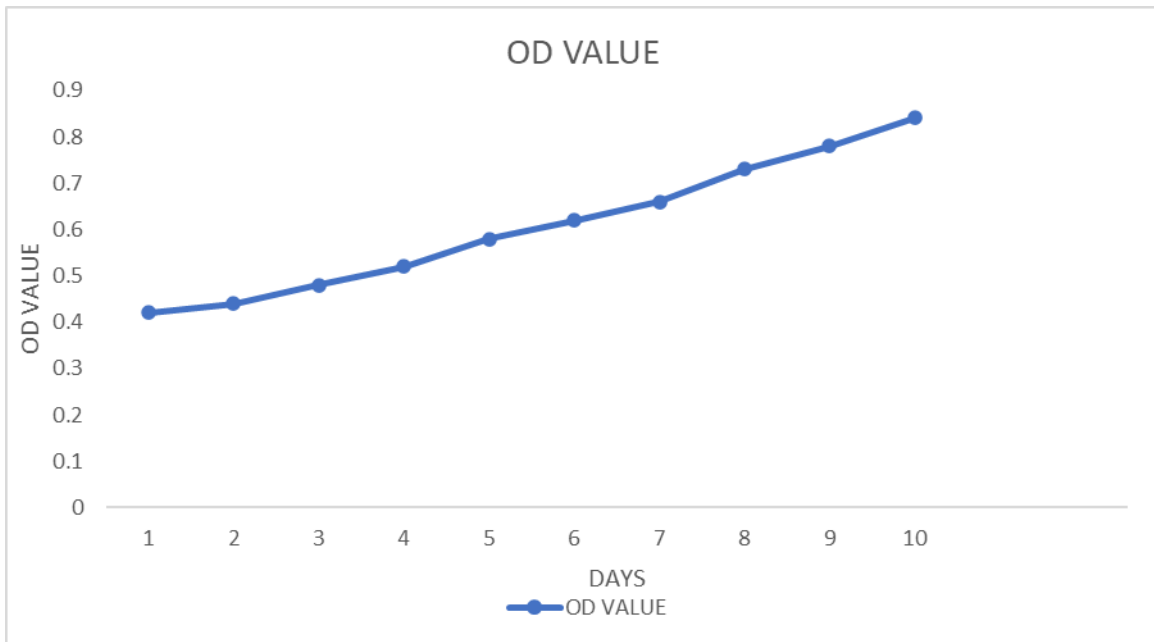


Fig.5 Immobilized *Spirulina platensis* algal beads



Fig.6 Waste water effluent



Fig.7 OD value for heavy metals

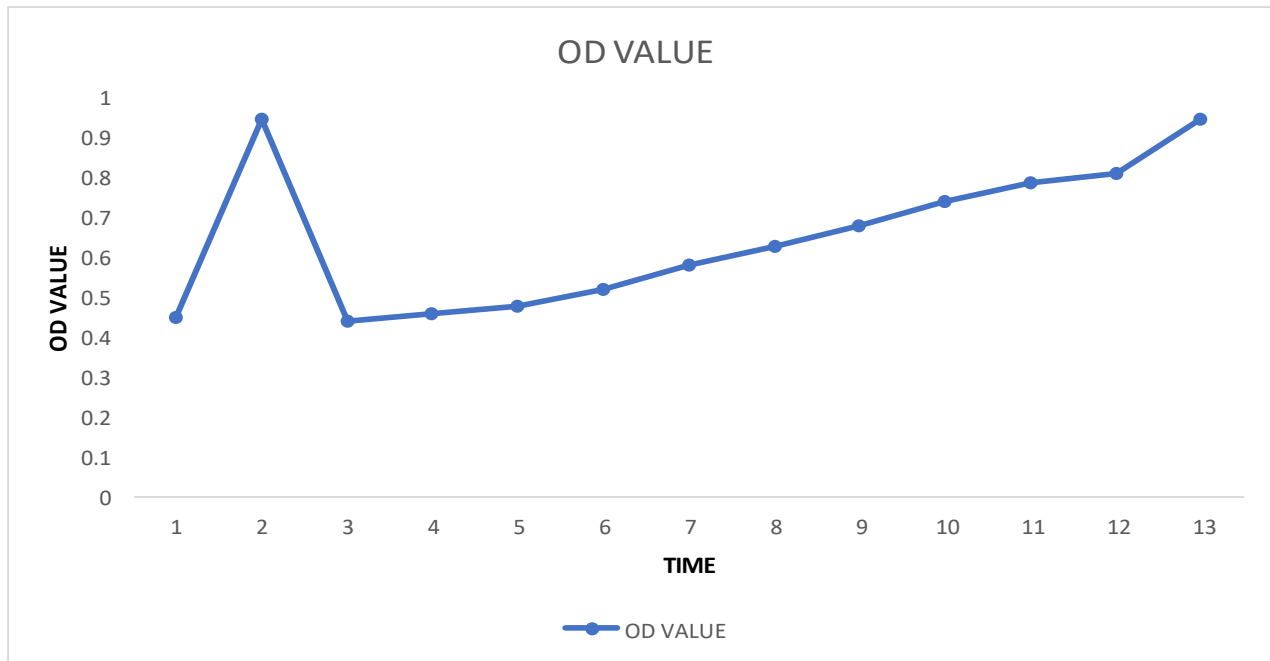


Fig.8 Heavy metal removal



Fig.9 pH analysis for lead degradation

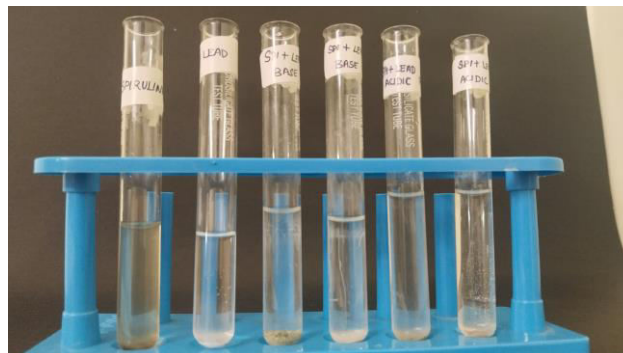


Fig.10 Immobilized pellet for lead degradation

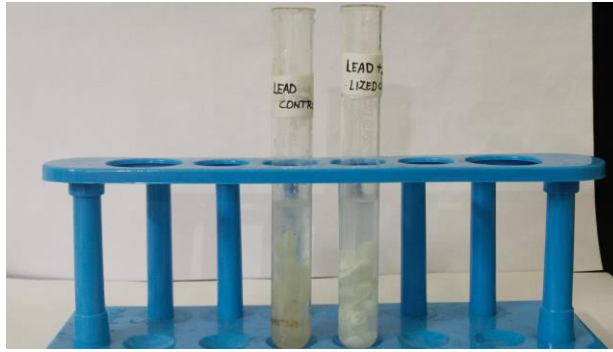
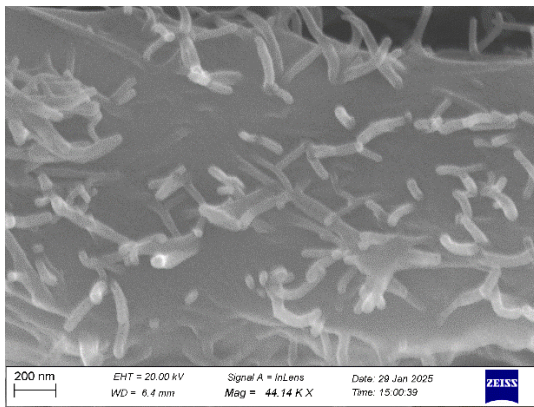
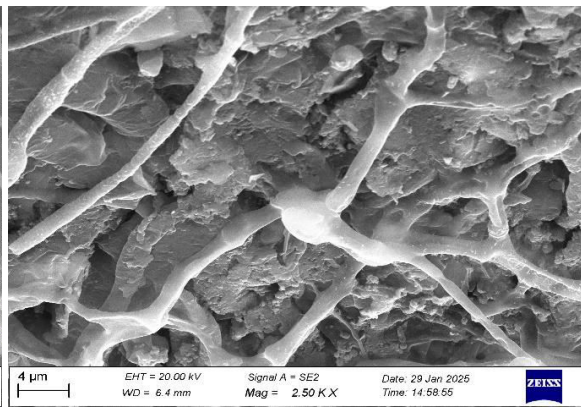


Fig.11a *Spirulina platensis* in SEM

Fig.11b Immobilized *Spirulina platensis* in SEM



11a



11b

Table.3 Physical properties of heavy metals before and after *S.platensis* pellet treatment

Physical Properties	Before Treatment	After Treatment
Colour	Slight pale yellow	Greenish
Odour	Foul smell	Slight algae smell
Foaming	5 cm	2 cm
Clarity	20%	80% improvement

Table.4 Physico-Chemical properties of effluent before and after *S.platensis* beads treatment

Physico-chemical properties	Before Results	After Results
pH	6.2	7.5
Dissolved oxygen	2.5 mg/l	6.8 mg/l
Biological oxygen Demand	180 mg/l	40 mg/l
Chemical oxygen demand	400mg/l	100 mg/l
Dissolved solids	1200 mg/l	950mg/l
Total suspended solids	250 mg/l	70 mg/l

Table.5 Heavy metals in Effluent by AAS

Heavy Metals	Before treatment(mg/l)	After treatment(mg/l)
Lead(Pb)	0.45	0.22
Mercury(Hg)	0.02	BLQ
Arsenic(As)	0.1	BLQ
Cadmium(Cd)	0.05	BLQ
Chromium(Cr)	0.3	0.25
Zinc(Zn)	2	NIL
Copper(Cu)	1.5	NIL
Iron (Fe)	0.1	BLQ

BLQ – Below limit of quantification

Table.7 Atomic absorption spectroscopy results

Before	After
4.077mg/l	1.719mg/l

Table.8 Heavy metal pollution Index

Heavy Metals	C _i	S _i	W _i = 1/S _i	Q _i = (C _i /S _i) × 100	W _i × Q _i
Lead	0.45	0.05	20	900	18000
Mercury	0.02	0.001	1000	2000	2000000
Arsenic	0.1	0.01	100	1000	100000
Cadmium	0.05	0.01	100	500	50000
Chromium	0.3	0.01	100	3000	300000
Zinc	2	15	0.066	13.33	0.87978
Copper	1.5	1	1	150	150
Iron	0.1	3.00	0.333	3.333	1.1089

Table.9 Heavy metal Evaluation Index

Heavy Metals	C _i	S _i	HEI = C _i × S _i
Pb	0.45	0.05	9
Hg	0.02	0.001	20
As	0.1	0.01	2
Cd	0.05	0.01	16.66
Cr	0.3	0.01	6
Zn	2.0	15	0.67
Cu	1.5	1	0.75
Fe	0.1	3.0	0.033

Table.10 Hazard Quotients (HQs)

Heavy metals	$R_Q = MEC/PNEC$
Pb	9>1
Hg	20>1
As	2>1
Cd	16.66>1
Cr	6>1
Zn	0.67<1
Cu	0.75<1
Fe	0.033<1

Table.11 Heavy metal pollution Index

Heavy Metals	C_i	S_i	$W_i = 1/S_i$	$Q_i = (C_i/S_i) \times 100$	$(W_i \times Q_i)$
Lead (pb)	0.22	0.05	20	1.1	22
Mercury	BLQ	0.001	1000	BLQ	BLQ
Arsenic	BLQ	0.05	20	BLQ	BLQ
Cadmium	BLQ	0.003	333.333	BLQ	BLQ
Chromium	0.25	0.05	20	500	10000
Zinc	NIL	3	0.333	NIL	NIL
Copper	NIL	2	0.5	NIL	NIL
Iron	BLQ	3	0.333	BLQ	BLQ

*BLQ – Below limit of quantification

Table.12 Heavy metal Evaluation Index

Heavy Metal	$HEI = C_i \times S_i$
Pb	0.11
Hg	BLQ
As	BLQ
Cd	BLQ
Cr	0.0125
Zn	NIL
Cu	NIL
Fe	BLQ

Table.13 Hazard Quotient

Heavy metals	$RQ = MEC/PNEC$
Pb	0.11<1
Hg	BLQ
As	BLQ
Cd	BLQ
Cr	0.0125<1
Zn	NIL
Cu	NIL
Fe	BLQ

From this study, Effluent colour Slight pale yellow to Greenish, Odour also reduced from foul smell to slight algae odour. Foaming height 5 cm before and it reduce 2 cm. Clarity was improved around 80% from 20%. The pharmaceutical effluent after treatment the pH level was turned from acidic 6.2 to alkaline 7.5. Dissolved oxygen was 2.5 mg/l to 6.8 mg/l. BOD level reduced to 180mg/l to 40mg/l and COD level reduced to 400mg/l to 100mg/l. Dissolved solids level reduced from 1200mg/l to 950mg/l. The above findings was supported by Al-Gheethi *et al.*, 2014, from their study the strain was originally isolated from treated sewage effluents, demonstrating its adaptability to such conditions. The findings Suggests that *B.subtilis* 1556wTNC can be used to improve the quality of treated sewage by removing pharmaceutical residues, offering an alternative to conventional, often costly, wastewater treatment methods (WWTM).

From this Study, in heavy metal analysis Lead concentration was significantly reduced from 0.45mg/l to 0.22 mg/l. Also, four elements namely Mercury, Arsenic, Cadmium and Iron respectively 0.02, 0.1, 0.05 and 0.1 mg/l concentrations were reduced into below level quantity. The above findings was supported by Birungi *et al.*, 2014 and they proposed that the impact of initial Lanthanum concentrations and found that adsorption efficiency decreased at higher concentrations due to saturation of binding sites.

The algae's reusability was tested through multiple cycles, demonstrating their potential for sustainable lanthanum recovery (Birungi *et al.*, 2014). This research underscores the feasibility of using freshwater algae as biosorbents for rare earth element recovery, paving the way for greener, cost-effective metal remediation technologies.

In this study, Heavy metal removal study was further conducted for Lead. For the same Lead acetate (1g/100ml) incorporated with Zarrocks medium and applied for immobilized *S.platensis* cultivation. After incubation for 7 days the filtrate was collected and analyzed through Atomic Absorption Spectroscopy. The results showed lead concentration before treatment as 4.077mg/l and after treatment 1.719mg/l. The above findings was supported by Zinicovscaia *et al.*, 2015 utilized Atomic absorption spectrometry (AAS) to analyse the elemental content of *S. platensis* biomass and the metal concentrations in industrial effluents. The results demonstrate a rapid adsorption rate, with chromium (initial concentration: 9.4 mg/L) being

removed significantly within the first 15 minutes, while nickel (initial concentration: 14.1 mg/L) was absorbed at a rate of 66% within an hour. The research suggested that *S. platensis* not only effectively removes chromium and nickel but also accumulates other metals such as iron, zinc, and barium, indicating its potential for multi-metal removal applications. Factors influencing biosorption efficiency, were including pH, metal concentration, and competition among metal ions. The findings supported the development of green technologies for water purification, emphasizing the feasibility of *S. platensis* as a sustainable alternative for heavy metal removal in industrial wastewater treatment,

Further SEM analysis was performed analysis revealed noticeable morphological changes on the surface of *Spirulina platensis* after exposure to heavy metals. The untreated cells exhibited a smooth, intact surface, while the treated samples showed irregularities, surface roughness, and the presence of particulate deposits, likely corresponding to absorbed heavy metal ions.

This finding is quite similar to the key mechanisms include, Adsorption on Cell Surface, Ion Exchange, Precipitation. Intracellular Uptake although more relevant for living cells, some metal ions can penetrate the cell wall and accumulate inside the biomass (Gunatilake S K., 2015). Factors which affect Biosorption, pH, Temperature, higher concentration reducing adsorption efficiency. Different biomaterials exhibit varying binding capacities depending on their functional groups, surface area, and porosity. The paper categorizes biosorbents into different groups based on their origin, microbial Biomass Includes bacteria, fungi, and algae, Agricultural Waste, Industrial By-products.

The results of this study concluded that lead and chromium were the most effectively removed heavy metals, as confirmed by the Heavy metals Index (HMI) for spirulina platensis immobilized pellets. This suggested a high affinity between the immobilized microalgae and these specific metal ions, potentially due to their ionic size, charge, and binding behaviour.

The enhanced removal efficiency could also be attributed to the functional groups present on the microalgal cell walls, which may favour the adsorption of lead and chromium. These findings also reported significant reductions in these metals using similar bioremediation techniques. However, the variability in removal rates for other metals highlighted need more targeted samples to be included further.

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